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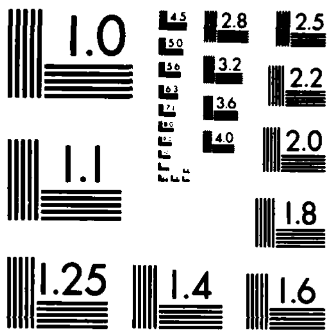

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EMISSION THRESHOLD FOR CERENKOV RADIATION

by

John R. Neighbours, Fred R. Buskirk and
Xavier K. Maruyama

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Technical Report

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EMMISSION THRESHOLD FOR CERENKOV RADIATION

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ABSTRACT

As a consequence of the relaxation of the phasing condition between the moving charge and radiated wave for finite beam lengths, the Cerenkov peak is broadened and the threshold energy is lowered. A criterion for the threshold energy is developed which is applicable to charged beams consisting of a single charge bunch of finite size, as well as beams consisting of periodically repeated bunches.

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INTRODUCTION

In previous work[1] we have given a form for the Cerenkov radiation from periodic electron bunches propagating in a homogeneous medium. The method involved construction of the Fourier components of the field which in turn led to the Poynting vector expressed as harmonics of the basic electron beam frequency. The important results were that the Cerenkov cone angle is shifted substantially beyond the ordinary Cerenkov angle θ_c, ($\cos\theta_c = (n\beta)^{-1}$) and broadened so that a significant fraction of the power radiated appears at angles other than θ_c. As either frequency or beam length increases, the cone angle was found to approach θ_c with an increasing fraction of the total radiation being radiated at that angle.

In a second paper[2], we showed preliminary experimental data and the results of calculations for X and K band microwave Cerenkov radiation produced by the electron bunches from an S band 100 Mev Linac propagating in air. These results as well as other unpublished ones are in agreement with the predictions of reference 1.

Subsequently we discussed several aspects of the expected Cerenkov radiation from an intense electron beam[3], and the emission threshold[4] for radiation in brief reports. The onset of Cerenkov radiation was ascribed to a relaxation of the phase matching condition between the charge and the wave and the effect has been investigated theoretically and experimentally in the optical region.[5,6,7]

Recently[8] we have corrected an error appearing in the appendix of reference 1 and have shown that the radiated energy from a single charge bunch has the same form as the radiated power from a beam of periodic bunches. Consequently the results of this paper are applicable to both.

The main purposes of this paper are:

(1) to amplify our remarks concerning the effects of a finite electron beam path on the sharpness of the radiation pattern,

(2) to show in detail how the energy threshold for the onset of Cerenkov radiation is affected by the electron beam path length,

SHARPNESS OF THE MAIN RADIATION LOBE

From Eq. (4) of reference 2, the power per unit solid angle radiated by a periodic charged particle beam of charge q per bunch in propagating a finite distance L is

$$W(\nu, \hat{n}) = \nu_0{}^2 Q R^2 \qquad (1)$$

where Q is the constant

$$Q = \frac{\mu c q^2}{8\pi^2} \qquad (2)$$

The radiation function is

$$R = kL \sin\Theta \; I(u) \; F(\vec{k}) \qquad (3)$$

and the parameters are

$$u = \frac{kL}{2} (\cos\Theta_c - \cos\Theta) \qquad (4)$$

$$I(u) = \frac{\mathrm{Sin}u}{u} \qquad (5)$$

The ordinary Cerenkov angle is given by $\cos\Theta_c = (n\beta)^{-1}$, $\vec{k}$ is the wave vector of the emitted radiation in the medium ($k = \omega/c$), and $F(\vec{k})$ is the dimensionless form factor, i.e. the Fourier transform of an individual charge bunch is q $F(\vec{k})$. The fundamental frequency of the periodic electron beam is ν_0 and c is the velocity of electromagnetic radiation in the medium. From (1), (3) and (5) it is apparent that the maxima in the radiation pattern occur at the extreme values of R and that the minima in W are true zeros; occuring when u is equal to an integral multiple of π. The largest value of I(u) occurs at Θ_c but the peak of the

main radiation lobe is shifted away from this angle by the presence of the other factors in (3). If the form factor is slowly varying in the region of Θ_c, the maximum value of W is shifted upward from Θ_c as a result of the $\sin^2\Theta$ factor. Fig. 4 and Fig. 5 of reference 2 show the main radiation lobe along with several subsidiary ones and show how all of these peaks shift with frequency and beam length.

It is difficult to deal analytically with the principal maximum of W even if F(k) has a relatively simple form. But regardless of the exact shift of the maximum away from Θ_c, the diffraction function I(u) always has zeros at $u = \pm \pi$. Consequently these limits restrict the peak value of W to lie between the Θ values determined by these zeros in I(u) assuming that these values of u correspond to physical values of Θ. Substituting $\pm\pi$ into (4) gives

$$\cos\Theta_1 = (n\beta)^{-1} + \eta^{-1} \quad (u=-\pi) \tag{6}$$

$$\cos\Theta_2 = (n\beta)^{-1} - \eta^{-1} \quad (u=+\pi) \tag{7}$$

for the upper (Θ_2) and lower (Θ_1) bounds of the main peak. Although W and R are given in terms of the wave vector, it is more convenient for what follows to deal with the radiation wavelength. Here λ is the wavelength of the Cerenkov radiation propagating in a medium with index of refraction n, and $\eta=\frac{L}{\lambda}$, is the beam length measured in units of that wavelength.

The behavior of the main radiation lobe, bounded by the angles Θ_1 and Θ_2, depends on the constants $n\beta$ and η, as shown by (6) and (7). It is obvious that as $\eta \to \infty$, the lobe narrows and

Θ_1 and Θ_2 both approach Θ_c, assuming, of course, that $n\beta > 1$ and Θ_c is defined. In this limit of an infinite medium, the radiation all appears at the Cerenkov angle.

In the other extreme, as η becomes smaller, diffraction spreads out the main lobe, and θ_2 increases from Θ_c and eventually becomes 180° for the value η_2 of the beam length parameter, where

$$\eta_2 = n\beta(n\beta + 1)^{-1} \tag{8}$$

Similarly, as η decreases, Θ_1 diminishes and becomes zero for $\eta = \eta_1$, where

$$\eta_1 = n\beta(n\beta - 1)^{-1} \tag{9}$$

One should note that η_2 is larger than η_1, and that η_1 varies considerably depending on the value of $n\beta$. For large $n\beta$, η_1 approaches 1; for $n\beta$ only slightly greater than one, η_1 is quite large. For example, 100 Mev electrons in air ($n\beta$ = 1.000255) have an η_1 value of 3920 while the same electrons in water ($n\beta$=1.333) have an η_1 value of 4.

For beam lengths shorter than η_1 only the upper bound has physical reality. This does not mean that a Cerenkov radiation peak does not occur for these short beam lengths, but only that the peak bound suggested by (6) is inapplicable and that the lower bound on the peak angle is zero.

Behavior of the two bounds is shown in Fig. 1 for 100 Mev electron bunches propagating in air (Θ_c = 1.3°) and water (Θ_c = 41.4°). For both materials, the angular difference ($\Theta_2 - \Theta_1$) is

large for relatively short beam paths but as η increases, the difference diminishes and both radiation patterns approach a δ like function centered about Θ_c.

As mentioned earlier, the main radiation peak is sensitive to the form factor so that it is difficult to determine Θ_m, the value of Θ for which the radiated power is a maximum, except by numerical studies. Fig. 1 also shows such numerical results for air, obtained from the calculations which led to Fig. 7 of Ref. 2. Taking the lower bound to be zero when Θ_1 does not exist, the graph shows that as a rule of thumb, Θ_m occurs roughly midway between the bounds Θ_1 and Θ_2. As was discussed in Ref. 2, the spreading of the main lobe of radiation about Θ_c is assymetric so that Θ_m is larger than Θ_c.

EMISSION THRESHOLD FOR COHERENT CERENKOV RADIATION

The above discussion showed that the upper and lower bounds and therefore the peak between them can change position, and Fig. 1 showed the effect of varying path length at constant electron beam energy, i.e. as η increases, Θ_2 and Θ_1, both move toward Θ_c.

Both the beam length and the beam energy (through β) affect the position of Θ_1 and Θ_2. At some finite η the radiation pattern is spread into a diffraction lobe bounded by Θ_2 and Θ_1. As the beam energy and thus β is reduced Θ_2, Θ_c, and Θ_1 become smaller. The angles may become non-physical because the governing equations contain cos Θ which formally may exceed unity. Since the inequality $\Theta_1 < \Theta_c < \Theta_2$ is always satisfied, it is possible to have Θ_1 only, be non-physical as discussed in the previous section, or to have both Θ_1 and Θ_c non-physical. In either case, the resulting main lobe of radiation extends from zero degrees to Θ_2 and this phenomenon may be termed sub-threshold Cerenkov radiation because it occurs for $n\beta$ less than (but usually close to) unity. More precise delineation of parameter ranges for $n\beta$ and η are discussed below.

We define the onset of the emission of Cerenkov radiation to be the situation when Θ_2 begins to enter the physical range. Then setting Θ_2=0 in (7) gives

$$n\beta = \eta\,(\eta+1)^{-1} \tag{10}$$

A plot of (10) is shown in Fig. 2. As the beam length increases, the product $n\beta$ first rises rapidly and then asymptotically approaches the value unity. Any value of $n\beta$ above the curve gives Cerenkov radiation with a peak position

dependent on the beam length. For values of $n\beta > 1$, the Cerenkov angle Θ_c is in the physical range. For values of $n\beta$ between the curve and unity, Θ_c is nonphysical but radiation with a well defined peak is still produced. Although Fig. 2 is a universal curve, it is useful and instructive to construct threshold energy curves for particular materials.

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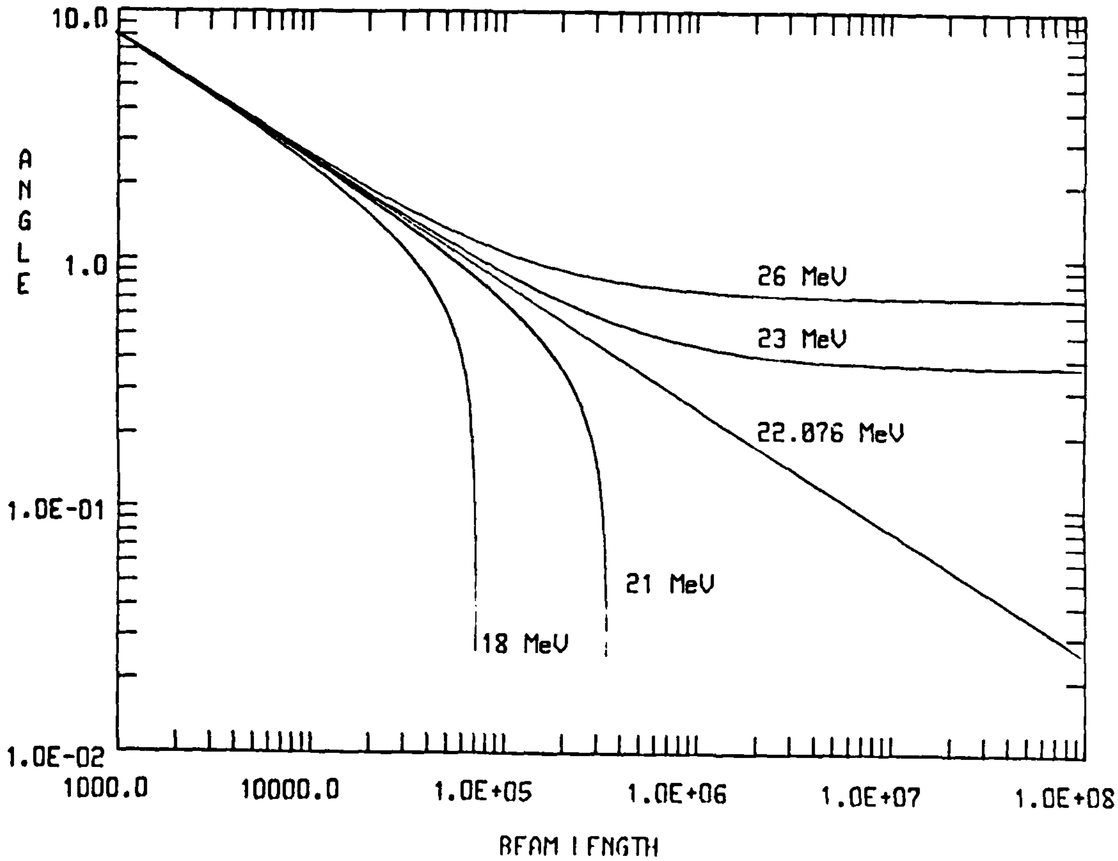

Fig. 4 Upper angular limit Θ_2 vs beam length η for electron bunches propagating in air ($n = 1.000268$).

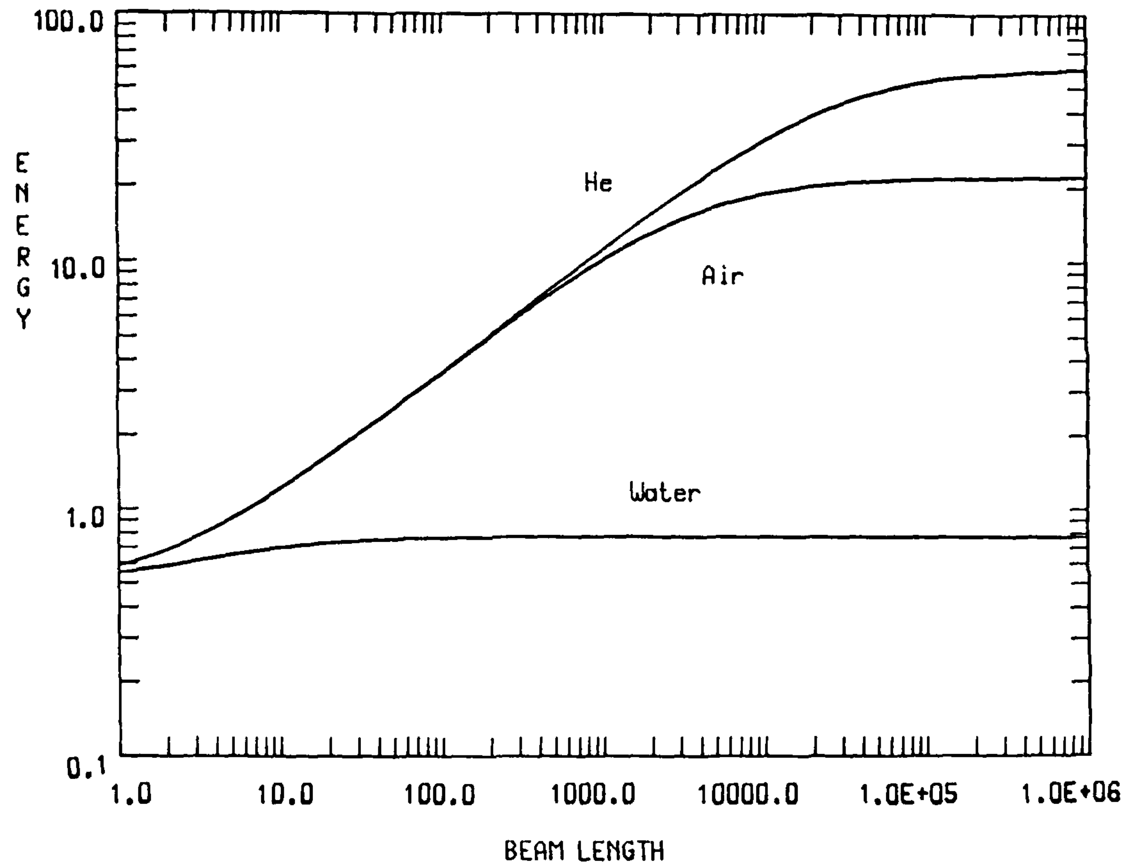

Fig. 3 Threshold electron bunch energies as a function of η for several different substances. At large values of η each curve approaches its respective E_T.

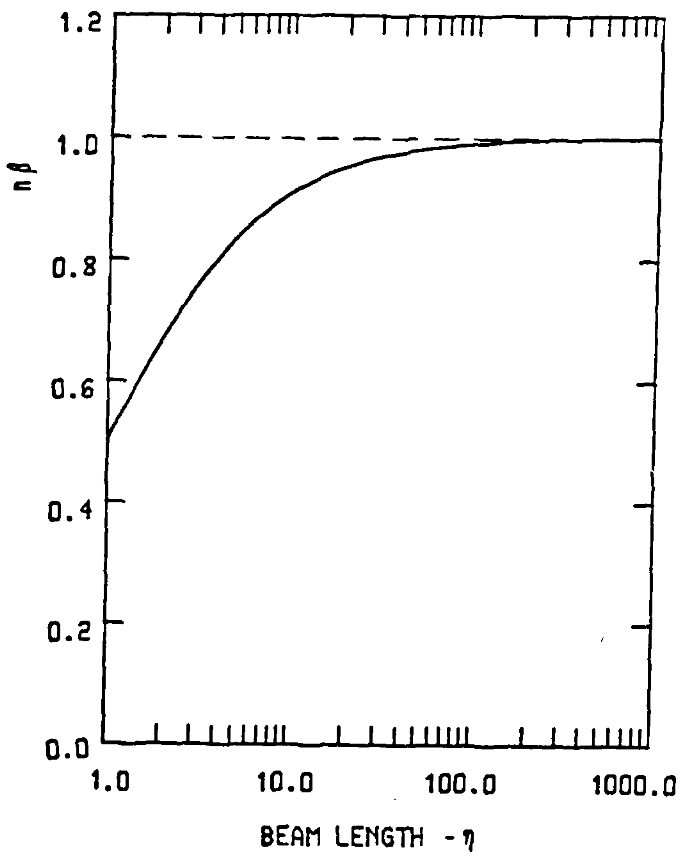

Fig. 2 Threshold value of nβ as a function of beam length η. A value of nβ above the curve will give rise to Cerenkov radiation Values of ηβ>1 will give rise to Cerenkov radiation for all values of η.

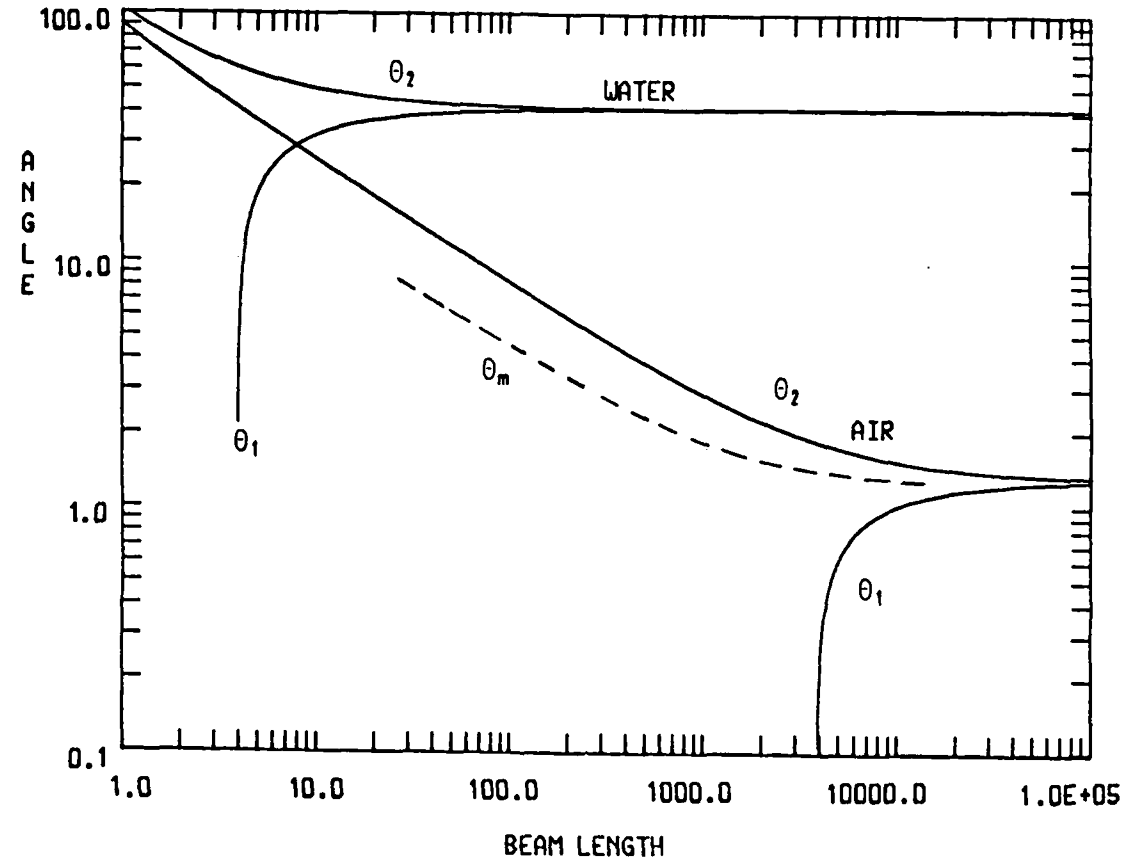

Fig. 1 First diffraction lobe angular limits Θ_2 and Θ_1 as a function of beam length η for 100 MeV electron bunches. The dashed curve marked Θ_m is the calculated angular value at which the peak of the main lobe occurs. (Values were obtained from the calculations leading to Fig. 7 of reference 2).

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The criterion for emission threshold came from the requirement that Θ_2, the null of the main diffraction lobe, should be in the physical regime. Similarly, a criterion for "fully developed emission" can be derived by determining the beam energy necessary to have Θ_1 in the physical range. The result seems of dubious value, since for short beam lengths its quite possible to have an intense Cerenkov peak even though the fully developed emission criterion is impossible to satisfy.

The results for a single charge bunch are the same as for a set of spatially periodic bunches except that the radiated quantity is different. As the beam length increases the radiated quantity (energy or power) increases in magnitude with a concommitant narrowing of the main radiation lobe, and the energy threshold rises to that required for an infinite beam length.

As a final remark, it might be argued that the emission occuring below the usual Cerenkov threshold is not truly Cerenkov radiation because the conventional properties (i.e. a sharp threshold and emission at the angle Θ_c) are not required. But the argument in favor of retaining this name is that the radiation has the same polarization as Cerenkov radiation and the usual intensity and emission angle are approached in a continuous manner as the length parameter η approaches ∞. A detailed discussion of the radiation patterns above and below threshold will be given in a future report.

DISCUSSION

The main point of this paper is that the beam interaction length η affects the production of Cerenkov radiation in both the angular distribution of the radiation and the beam energy necessary to commence the process. Since η is the ratio L/λ, this means that both the actual beam length and the wavelength of the observed radiation can have influence.

In an optically dense medium such as water the main radiation lobe occurs at a rather large angle to the beam and the lobe broadening narrows quickly for η values greater than 20. In addition the threshold energy shows only a small variation.

Contrarily, in an optically thin medium such as gas, the lobe broadening persists over several decades before approaching the much smaller infinite beam length limit of Θ_C. Also, the threshold energy varies over several decades of η so that the onset of Cerenkov radiation is not sudden but rather a continuous increase.

These effects are most apparent at short beam lengths (say $\eta \sim 10$) and are of interest when observing microwave Cerenkov radiation produced by electron beams emerging from an RF Linac. Although a high energy, high intensity charged particle beam may be shielded by a plasma sheath, Cerenkov radiation and the associated broadening of the main lobe as a result of short beam lengths may arise from the transition regions at the ends of the beam.

RADIATION FROM A SINGLE CHARGE BUNCH

In Appendix A of reference 1 we gave the derivation of Cerenkov radiation from a single bunch of charge and (A12) gives the energy radiated per unit solid angle per unit angular frequency a. This equation is missing a factor of v^2 in the published version. When this factor is included, and the energy radiated per unit solid angle per unit frequency ν is written as $E(\nu, \hat{n})$ in order to avoid confusion with $W(\nu,n)$, the result is

$$E(\nu, \hat{n})d\nu = Q R^2 d\nu \tag{15}$$

Since both $E(\nu,n)$ and $W(\nu,n)$ both contain the same dimensionless factor R, all of the analysis of the previous sections applies equally to $E(\nu,n)$. The difference is only between the quantities radiated; power in one case and energy in the other.

well above E_T is shown in Fig. 1. For θ_2, the limiting value of beam length denoted η_L is

$$\eta_L = n\beta\,(1-n\beta)^{-1} \tag{14}$$

which gives a non realistic (negative) value for beam energies above E_T and a positive value for energies below E_T.

Consequently the behaviour of the curves is different for energies less than E_T. For these energies, (9) gives a negative result for η_1 and therefore for these energies only θ_2 is physical, and only for beam lengths <u>less</u> than η_L.

Fig. 4 shows Θ_2 as a function of η for beam energies near the calculated value of E_T = 22.076 MeV. For beam energies above E_T, the Θ_2 curve is aysmptotic to Θ_c at large values of η. In contrast, for beam energies below E_T, the Θ_2 curves go rapidly to zero at η_L.

The interpretation of the curves in Fig. 3 is as follows: If a given physical situation is represented as a point with coordinates E and η on the graph, when that point lies below the curve, Cerenkov radiation is not produced. Above the curve, but below the threshold energy for infinite path, is the transition region in which the radiation peak continuously increases in size but changes position only slightly. In this region $n\beta<1$, only Θ_2 may exist, and casual analysis would not predict Cerenkov radiation since $\cos\theta_c = (n\beta)^{-1}$ has no solution for θ_c. For energies greater than the infinite beam length threshold energy, in addition to Θ_2, Θ_1 may exist and the main lobe is prominent. In this region and the transition region, the main lobe is broadened by diffraction according to the value of η.

Fig. 1 showed how the width of the main lobe varied with the beam length of 100 MeV electron bunches. Curves for other beam energies above $E_T(\eta=\infty)$, the threshold for inifinte beam length are similar except displaced. As the beam energy decreases, the Cerenkov angle Θ_c which is the asymptote of the Θ_2 and Θ_1 curves, is lowered, and consequently is approached at increasingly larger beam lengths. For beam energies very close to $E_T=\gamma_t(\eta=\infty)E_o$ the asymptotic nature is not evident until extremely long beam lengths. (This behavior is not surprising since at E_T the Cerenkov angle is zero at infinite beam lengths).

The limits on beam length for either θ_1 or θ_2 to be physical are obtained from (6) and (7) by setting the angle equal to zero. The limiting beam length for θ_1 to be nonphysical is η_1 as given by (9) and the approach of θ to this limit for beam energies

Since many charged particle beams are composed of electrons it is convenient to display threshold energy (instead of γ_t) as a function of beam length as is shown in Fig. 3. Plots for three materials with different indices are shown: all approach 0.511 MeV for short beam lengths and approach the value given by (12) for long beam lengths.

Due to its relatively large index of refraction, the variation of the threshold emission energy for water is much smaller than for the two gases, (0.511 to 0.77 Mev) and consequently the emission threshold for water is relatively constant independent of particle beam length. For gases, the variation is large - over two decades in the case of helium. This large variation in threshold energy is interesting since it seems not to be well known that Cerenkov radiation can be produced by short beams with energies substantially below the threshold energy for infinite path length. For example, a 10 MeV beam with a length of η = 10 would be well above the threshold for either helium or air but a simple analysis would not predict Cerenkov radiation for beam energies so much lower than the infinite beam length threshold values of 22.1 and 60.2 Mev for helium and air respectively.

Since the thresholds for the two gases are different at the larger lengths, it is possible to find sets of parameters where one gas is favored. A beam with an energy of 18 Mev and a length $\eta \sim 4\times10^3$ would produce Cerenkov radiation when propagating in air but not in helium.

Using the usual relation between β and γ, (10) can be written in terms of γ_t, the value of γ necessary for the onset of Cerenkov Radiation.

$$\gamma_t(\eta) = [1 - \frac{1}{n^2(1+\eta^{-1})^2}]^{-1/2} \qquad (11)$$

This gives the required energy $E_t = \gamma_t E_o$ for the onset of emission in terms of the index of refraction n and the beam length η.

Limiting values of (11) can be obtained for very long and very short beam lengths. For infinite beam length

$$\gamma_t(\eta=\infty) = [1 - \frac{1}{n^2}]^{1/2} \qquad (12)$$

which decreases and approaches the value of 1 as n increases. If n~1 as for most gases, the threshold value of $\gamma_t(\eta=\infty)$ is large and depends critically on the particular value of n. Then, writing the index of refraction as $n=1+\delta$, the threshold value of $\gamma_t(\eta=\infty)$ is proportional to $\delta^{-1/2}$ in the limit of small δ

$$\gamma_t(\eta=\infty) \cong (2\delta)^{-1/2} \qquad (13)$$

From (13), the threshold energy at infinite beam length $E_T = E_o \gamma_t(\eta=\infty)$ is 22.1 Mev for electrons in air.

For short beam lengths, (11) shows that, as $\eta \rightarrow 0$, $\gamma_t(\eta=0) \rightarrow 1$ independent of the value of n. Thus for very short paths, there is no threshold. This may be seen from (10) where as $\eta \rightarrow 0$, the value of β at threshold also approaches zero.

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